Bentonite-Polymer Composite Geosynthetic Clay Liners for Heap Leach Liners

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Abstract

Hydraulic conductivity of four commercially available bentonite-polymer composite (BPC) geosynthetic clay liners (GCLs) and one conventional sodium bentonite (NaB) GCL was evaluated using a synthetic copper heap leach solution. The BPCs were comprised of granular NaB dry-blended with granular polymer. Each BPC contained a unique proprietary polymer. The NaB GCL was comprised of the same bentonite as the BPCs. Tests were conducted under two different stress scenarios. In the low stress scenario, testing began at low initial confining stress (20 kPa) simulating a thin layer of ore on the heap leach pad, followed by a ramp up to 600 kPa. The high stress scenario began with a higher initial confining stress (200 kPa) simulating a 10-m-thick layer of ore rapidly placed on the pad, followed by the same ramp up to 600 kPa.

Permeation with the copper heap leach solution adversely affected the NaB GCL, with the hydraulic conductivity exceeding 10^{-9} m/s for all but one case (200 kPa stress under high initial stress condition). The BPC GCLs had much lower hydraulic conductivities ($< 9.1 \times 10^{-11}$ m/s), indicating that BPC GCLs can be more effective as liners for copper heap leach solutions than NaB GCLs. Hydraulic conductivity of the BPC GCLs varied with type of polymer and decreased modestly with increasing effective stress. The BPC GCLs permeated with higher initial stress had lower hydraulic conductivity compared to those initially permeated at low initial stress, indicating that high initial stress affords protection for BPC GCLs. Similar protection was not realized for the NaB GCL. Swell index (SI) and active water content (AWC) were evaluated as indices of hydraulic conductivity of the BPC GCLs. Neither index was an effective indicator of hydraulic conductivity.

Introduction

Geosynthetic clay liners (GCL) are used in lining systems for heap leach facilities to collect leach solution draining from the ore. Conventional GCLs are comprised of a thin layer of sodium (Na) bentonite granules sandwiched between two geotextiles that are bonded together by needle punching or stitching. To achieve low hydraulic conductivity, the bentonite granules must swell sufficiently during hydration to fill the intergranular pores (Figure 1a) and seal off the needle punching fiber bundles. If swelling is insufficient, larger pores remain and a GCL will have high hydraulic conductivity (Figure 1b). The hydraulic conductivity of GCLs with Na bentonite can range six orders of magnitude or more depending on how much the bentonite granules swell (Jo et al., 2001; Kolstad et al., 2004; Tian et al., 2016; Chen et al., 2018).

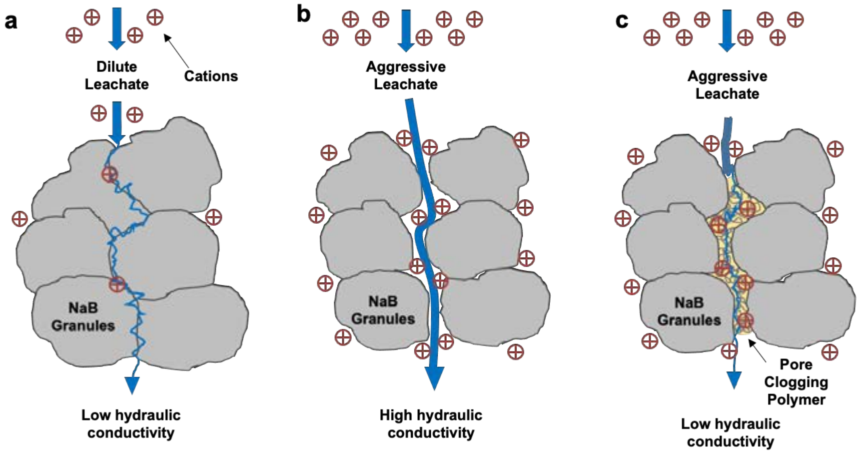

Figure 1: Swelling of Na bentonite granules in conventional GCL closes intergranular pores yield low hydraulic conductivity (a), suppressed swell of granules leaves by aggressive leachate intergranular pores open yielding high hydraulic conductivity (b), and polymer gel in BPC clogs intergranular pores yielding low hydraulic conductivity (c)

The swelling of bentonite is highly sensitive to the geochemistry of the solution to be contained. Solutions with higher ionic strength, a preponderance of polyvalent cations (charge of +2 or higher), or extreme pH, often referred to as “aggressive solutions,” tend to suppress bentonite swelling, resulting in a GCL with hydraulic conductivity that may be too high for the barrier application of interest (Jo et al., 2001; Kolstad et al., 2004; Scalia and Benson, 2016). In such cases, a GCL containing a bentonite-polymer composite (BPC) can be suitable (Scalia and Benson, 2016; Tian et al., 2019; Chen et al., 2019; Norris et al., 2022; Tan et al., 2022).

BPC GCLs contain a mixture of bentonite and polymer granules. When the BPC hydrates, the polymer granules form a gel that clogs open intergranular pores in the hydrated bentonite, resulting in narrow and tortuous flow paths and low hydraulic conductivity (Figure 1c). The low hydraulic conductivity persists provided the hydrated polymer remains in the intergranular pores and retains a gel structure. However, the rheology of polymer gels is sensitive to the geochemistry of the hydrating solution, and some gels are eluted from the intergranular pore space if their surface tension is altered, or the gel viscosity diminishes. If elution is significant, the hydraulic conductivity of a BPC GCL can increase significantly (Scalia and Benson, 2016; Tian et al., 2019; Norris et al., 2022).

In this study, four commercially available BPCs and one conventional Na bentonite (NaB) GCL were hydrated and permeated with a synthetic copper heap leach solution that had low pH and contained predominantly divalent cations. The NaB GCL and the BPCs were provided by Solmax Inc. The BPCs were comprised of granular Na bentonite dry-blended with granular polymer. Each BPC had a unique polymer. The NaB GCL was comprised of the same bentonite used in the BPCs. The polymers used in the BPC and the polymer loading are proprietary to the GCL manufacturer and were not divulged to the investigators. Tests were conducted under different loading conditions representing different overburden pressures in the heap leach facility. Findings from these tests are described in this paper.

Materials

Geosynthetic clay liners

Mock BPC GCLs were prepared by placing 5 kg/m^2 of BPC comprised of dry blended NaB and granular polymer between a nonwoven geotextile and a woven-nonwoven composite geotextile. All materials were provided by the manufacturer. The composite geotextile consists of a woven silt film geotextile bonded to a nonwoven geotextile, with the silt film geotextile internal to the GCL. The NaB GCL was provided by the same manufacturer and consisted of 4.8 kg/m^2 of granular bentonite sandwiched between the aforementioned geotextiles, which were bonded by needle punching.

Synthetic copper heap leach solution

A typical copper heap leach solution was identified using data on the geochemistry of five copper heap leach solutions reported by Ghazizadeh et al. (2018). The geochemistry of these solutions was described in terms of the two master variables affecting the hydraulic conductivity of NaB GCLs, ionic strength (I):

$$I = \sum_{i=1}^{n} C_i z_i^2 \qquad \text{(Equation 1)}$$

and RMD:

$$RMD = \frac{M_M}{\sqrt{M_D}} \qquad \text{(Equation 2)}$$

Where:

C_i is the concentration of the ith ionic species in the solution,

z_i is the valence of the ith species,

M_M is the total molarity of monovalent cations in solution, and

M_D is the total molarity of polyvalent cations in solution.

A recipe was created to represent the median concentration of the copper heap leach solutions reported in Ghazizadeh et al. (2018), with I = 0.689 M and RMD = 0.020 $M^{0.5}$ (Table 1). The recipe was checked for charge balance and over-saturation using Visual MINTEQ. The pH was adjusted to 2.2 by titration with sulfuric acid. The final solution had an electrical conductivity (EC) of 0.2 S/m and an anion ratio (A_r = molar ratio of chloride to sulfate) of 0.59.

Table 1: Recipe for synthetic copper heap leach solution

Constituent	Concentration (g/L)
$Al_2(SO_4)_3$-$18H_2O$	9.62
$CaCl_2$	1.46
$CuCl_2$	0.18
KCl	0.13
$MgCl_2$-$6H_2O$	5.05
$MgSO_4$	8.77
$MnSO_4$-H_2O	1.16

Methods

Swell index and active water content

Swell index (SI) and active water content (AWC) tests were conducted on the NaB (SI only) and the BPC (SI and AWC) using the copper heap leach solution for hydration. Swell index tests were conducted in accordance with ASTM D5890 and the procedures in Tan et al. (2022). The NaB and BPCs were ground in a motorized grinder (Retsch RM 200, Haan, Germany) until all particles passed the No. 100 sieve and at least 65% passed the No. 200 sieve. Two grams of the ground and dry NaB or BPC were gradually added to a graduated cylinder containing 90 mL of copper heap leach solution. The cylinder was filled to 100 mL after the bentonite was added. The swell volume at 24 hours was recorded as the swell index.

Active water content (AWC) tests were conducted following the methods in Geng et al. (2022). BPCs were placed in 50-mL centrifuge tubes along with the copper heap leach solution at a 1:10 solid-to-liquid ratio. The tubes were tumbled end-over-end for 48 hours at 30 RPM, and then centrifuged at 10,000 RPM for 20 minutes in a Beckman Allegra 25R centrifuge (Beckman Coulter, Palo Alto, California) with a centripetal acceleration of 25,000 g. The solution separated from the BPC mixture during centrifugation was spiked with Rhodamine dye to identify the interface between the solution and the hydrated polymer gel and strongly bonded bentonite. Water content of the hydrated polymer gel and strongly bonded bentonite was measured at 105°C using ASTM D2216, and reported as active water content.

Hydraulic conductivity

The GCLs were hydrated and permeated with the synthetic heap leach solution in flexible-wall permeameters in general accordance with the procedures described in ASTM D6766. The test specimens had a diameter of 150-mm and were placed in the permeameters between two heavy nonwoven geotextiles used to spread flow uniformly across the surface of the specimen. NaB GCL specimens were trimmed from a GCL roll using a sharp razor knife, with deionized (DI) water applied around the edge to prevent loss of bentonite during trimming. Mock GCLs were prepared from the BPCs and geotextiles, as described previously. All GCL specimens were oriented in the permeameter with the nonwoven geotextile on the upstream side and a composite geotextile on the downstream side of the GCL. The woven slit-film geotextile was on the interior face of the downstream side of the GCL. To prevent sidewall leakage, a layer of paste was smeared around the periphery of the test specimen, and a thin wedge of paste was placed along the periphery of the downstream surface of the GCL before the specimen was sealed with the flexible membrane. The paste was prepared with NaB or BPC and DI water. O-rings were used to seal the membrane to the pedestals.

Cell pressure was applied using tap water in the permeameter plumbed to a pressure panel board employing compressed air and an air-over-water interface to provide the desired cell pressure. The influent was contained in a burette and the outflow was collected in a 50-mL polyethylene container. The influent burette and the effluent container were both vented in a manner that maintained atmospheric pressure while minimizing evaporation. No backpressure was used to preclude unintended geochemical alterations associated with elevated pressure (i.e., Le Chatelier principle). Flow was oriented in the downward direction to simulate the field scenario. The specimens were hydrated with the heap leach solution for 48 hours with the cell pressure and influent head applied and the effluent valve closed (no hydraulic gradient). Permeation commenced after 48 hours of hydration by slowly opening the effluent valve.

Tests were conducted under two different stress scenarios: low and high initial confining stress. In the low initial stress scenario, testing began at low initial confining stress (20 kPa) simulating a thin layer of ore on the heap leach pad, followed by a ramp up to 600 kPa in seven increments (20 kPa to 50, 100, 200, 300, 400, 500, and 600 kPa) representing increasing ore thickness. The high initial stress scenario began with a higher initial confining stress (200 kPa) simulating a 10-m-thick layer of ore rapidly placed on the pad, followed by the same ramp up to as much as 600 kPa.

The two scenarios were evaluated to determine if higher stress prior to contact with solution provides additional protection of the GCL from adverse chemical interactions. In all cases, tests were required to reach the hydraulic and chemical termination criteria in D6766 before the stress was incremented to the next level. Hydraulic equilibrium was defined as steady flow and inflow equal to outflow per the criteria in D6766. Chemical equilibrium was defined as EC of the effluent within 10% of the EC of the influent per the EC criteria in D6766. Several of the tests are still being conducted. The most recent data at the time this paper was prepared are reported herein.

Results

A typical response of the NaB and BPC GCLs to permeation with the copper heap leach solution is shown in Figure 2 for low stress test (20 kPa) with the NaB and BPC GCLs. The hydraulic conductivity declines gradually as the bentonite swells (NaB GCL) and the polymer gel clogs pores (BPC GCL). An equilibrium hydraulic conductivity is reached in about 4 PVF for the NaB GCL and 2.0 PVF for the BPC GCL.

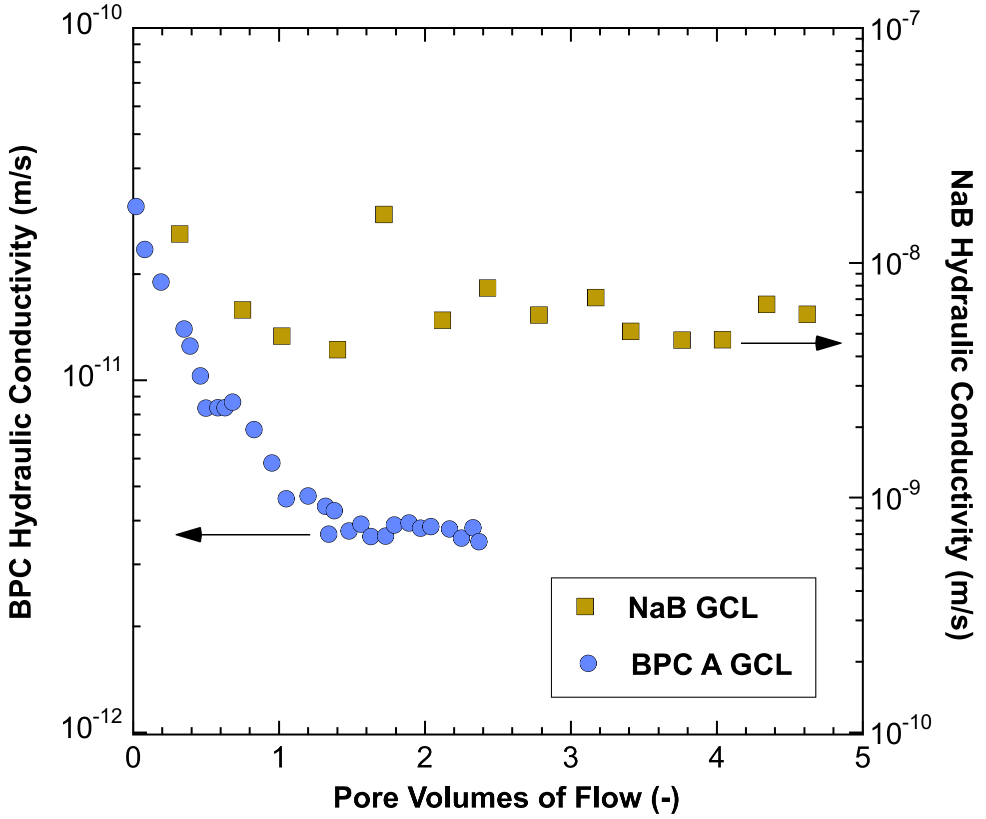

Figure 2: Typical response of NaB and BPC GCLs to permeation with copper heap leach solution. Tests conducted at 20 kPa effective stress with low initial stress

Hydraulic conductivities for the NaB and BPC GCLs are summarized in Table 2 and are shown as a function of effective stress in Figure 3. Hydraulic conductivities of the GCLs tested at low initial confining stress are shown in Figure 3 with solid symbols, whereas hydraulic conductivities of GCLs with high initial confining stress are shown with open symbols.

Table 2: Summary of hydraulic conductivity test conditions and outcomes

GCL	Initial stress (kPa)	Stress during permeation (kPa)	Pore vol. of flow	Test duration (d)	Hydraulic conductivity (m/s)
NaB	20	20	3.03	28.0	5.4×10^{-9}
		50	3.48	78.1	5.7×10^{-9}
		100	3.44	55.1	6.4×10^{-9}
		200	4.24	22.8	5.7×10^{-9}
		300	6.63	33.1	4.6×10^{-9}
		400	1.54	4.4	3.6×10^{-9}
		500	1.85	16.0	2.7×10^{-9}
		600	1.08	3.9	2.1×10^{-9}
BPC A	20	20	2.57	182.7	3.8×10^{-12}
		50	0.73	75.6	4.8×10^{-12}
		100	0.44	47.4	4.2×10^{-12}
		200	0.56	50.8	3.8×10^{-12}
		300	0.19	41.0	1.9×10^{-12}
		400	0.23	26.8	3.1×10^{-12}
		500	0.55	78.0	3.4×10^{-12}
		600	0.22	23.6	3.2×10^{-12}
BPC B	20	20	3.19	182.2	3.9×10^{-12}
		50	0.54	53.7	3.7×10^{-12}
		100	0.92	71.0	4.4×10^{-12}
		200	0.62	50.8	4.4×10^{-12}
		300	0.21	41.0	2.6×10^{-12}
		400	0.16	25.2	2.3×10^{-12}
		500	0.55	78.0	3.4×10^{-12}
		600	0.27	23.6	3.5×10^{-12}
BPC C	20	20	5.85	70.8	3.7×10^{-11}
		50	7.07	83.9	6.2×10^{-12}
		100	5.14	54.2	6.1×10^{-11}
		200	5.59	22.7	4.6×10^{-11}
		300	7.63	83.1	1.5×10^{-11}
		400	1.28	15.9	1.0×10^{-11}
		500	1.06	41.0	7.4×10^{-12}
		600	4.32	123.2	6.1×10^{-12}
BPC D	20	20	2.81	169.3	2.1×10^{-11}
		50	3.47	75.6	4.3×10^{-11}
		100	2.54	48.3	3.0×10^{-11}
		200	4.48	50.8	5.9×10^{-12}
		300	1.91	41.0	4.8×10^{-11}
		400	1.21	26.8	1.9×10^{-11}
		500	1.77	72.3	1.5×10^{-11}
		600	0.36	23.6	1.3×10^{-11}
NaB	200	200	4.41	171.2	6.7×10^{-10}
		300	6.42	68.1	2.0×10^{-9}
		400	0.79	4.4	1.8×10^{-9}
		500	2.24	17.0	3.2×10^{-9}
		600	1.41	3.9	2.5×10^{-9}

Table 2: Summary of hydraulic conductivity test conditions and outcomes (continued)

GCL	Initial stress (kPa)	Stress during permeation (kPa)	Pore vol. of flow	Test duration (d)	Hydraulic conductivity (m/s)
BPC A	200	200	0.71	240.4	8.1×10^{-13}
		300	0.19	141.0	7.3×10^{-13}
		400	0.07	26.8	8.3×10^{-13}
		500	0.14	103.8	6.2×10^{-13}
BPC B	200	200	0.75	240.4	1.0×10^{-12}
		300	0.33	148.0	1.3×10^{-12}
		400	0.29	113.6	1.1×10^{-12}
BPC C	200	200	0.95	240.4	2.4×10^{-12}
		300	0.69	151.2	2.4×10^{-12}
		400	0.15	26.8	1.9×10^{-12}
		500	0.44	103.6	1.8×10^{-12}
BPC D	200	200	1.26	240.4	2.5×10^{-12}
		300	0.86	151.2	3.3×10^{-12}
		400	0.20	26.8	2.6×10^{-12}
		500	0.70	103.8	2.5×10^{-12}

Hydraulic conductivity of NaB GCLs

The NaB GCL had hydraulic conductivity exceeding 10^{-9} m/s for all tests conducted with low initial stress, and for all but the first increment (200 kPa) for tests with high initial stress, indicating that the aggressive copper heap leach solution suppresses swelling of the NaB granules and closure of intergranular pores (Table 2, Figure 3). The high hydraulic conductivity of the NaB GCL to copper heap leach solution is consistent with the SI of the NaB, which was 9.1 mL/2g when hydrated in the copper heap leach solution and 34.9 mL/2g when hydrated in DI water. Hydraulic conductivities of the NaB GCL to the copper heap leach solution generally are too high for the GCL to be effective, indicating that liners for copper heap leach facilities require GCLs that are more chemically resistant to copper heap leach solutions.

Hydraulic conductivity of the NaB GCL tested at low initial stress increased slightly (1.2×) as the confining stress increased from the initial 20 kPa up to 50 kPa and then up to 100 kPa, which was unexpected. The hydraulic conductivity then decreased monotonically and gradually with increasing confining stress (Figure 3). The unexpected slight increase in hydraulic conductivity as the stress increased from 20 kPa suggests that the NaB GCL was not in geochemical equilibrium when the stress was increased, despite meeting the termination criteria in D6766. The increase in hydraulic conductivity at higher effective stress also corresponds to additional permeation, suggesting that slow rate-limited cation exchange between the solution and NaB may have been occurring, as reported in Jo et al. (2004; 2005; 2006). This effect was more significant for NaB GCLs with high initial stress, with the hydraulic conductivity increasing 4.7× as the effective stress was incremented upward from 200 kPa to 500 kPa, and only decreasing slightly as the stress was increased from 500 to 600 kPa. Moreover, any benefits of the initial high effective stress were ameliorated as the stress increased, with the NaB GCLs with low and high initial stress having essentially the same hydraulic conductivity at 500 kPa and at 600 kPa.

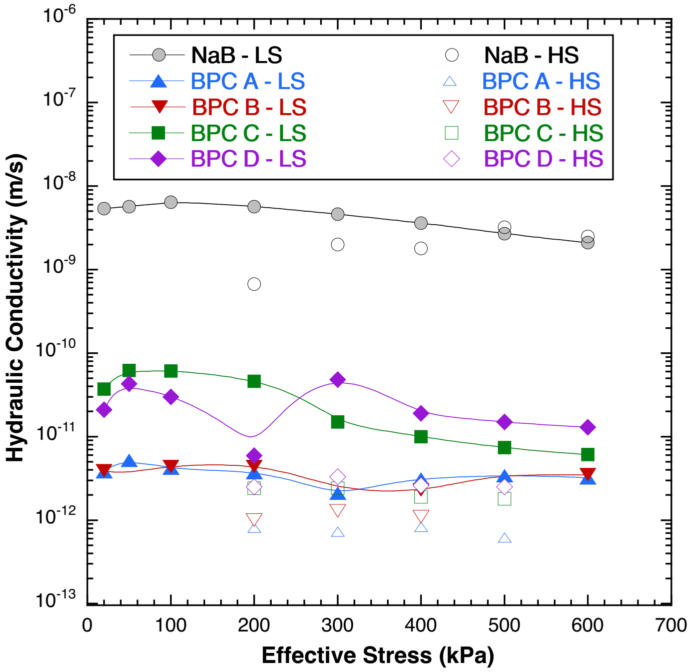

Figure 3: Hydraulic conductivity of NaB GCLs and BPC GCLs to copper heap leach solution as a function of effective stress for tests conducted at low (20 kPa) and high (200 kPa) initial stress

Hydraulic conductivity of BPC GCLs

Hydraulic conductivity of the BPC GCLs is also shown in Figure 3 as a function of effective stress for low and high initial stress. Hydraulic conductivities of the BPC GCLs with low initial confining stress are shown with solid symbols, whereas hydraulic conductivities of BPC GCLs with high initial confining stress are shown with open symbols. Much lower hydraulic conductivities (10^{-13} to 10^{-11} m/s) were obtained with the BPC GCLs than the NaB GCL (10^{-10} to 10^{-9} m/s), indicating that BPC GCLs can be more effective in liners for aggressive copper heap leach solutions.

For low initial confining stress, hydraulic conductivity of the BPC GCLs increases slightly (< 2×) as the confining stress is increased from 20 kPa up to as much as 100 kPa, and then decreases nearly monotonically with increasing confining stress. As with the NaB GCLs, the unexpected increase in hydraulic conductivity between 20 kPa and 100 kPa suggests that the GCLs were not in geochemical equilibrium, despite meeting the termination criteria in D6766 before the stress was increased. As the stress is increased further, the hydraulic conductivity diminishes gradually, with a reduction of at most 10-fold from the highest to low hydraulic conductivity. This suggests that the pore space is only changing modestly with increasing stress, and that the primary mechanisms contributing to low hydraulic conductivity (bentonite swelling and pore clogging by polymer) are established at the lowest stress.

BPC GCL D exhibited an unusual dip in hydraulic conductivity at 200 kPa, followed by an increase in hydraulic conductivity at the next increment in stress. This may indicate that the polymer is being re-distributed in the pore space when the stress is increased, that pores not filled with polymer at lower stress are closed as the stress increases, and/or polymer elution is occurring intermittently.

Effect of elevated initial stress

Hydraulic conductivities obtained from the low and high initial stress tests are compared in Figure 4. Hydraulic conductivities of the BPC GCLs with high initial stress were approximately 2 to 20-fold lower than BPC GCLs with low initial stress, with 5-fold lower being typical. All of the BPC GCLs with high initial stress had very low hydraulic conductivity, less than 3.3×10^{-12} m/s. The BPC GCLs with high initial stress also were nearly insensitive to the effective stress (Figure 3), with similar hydraulic conductivities obtained for stresses from 200 to 500 kPa. This suggests that larger pores are closed by the initial higher stress, providing some protection against higher hydraulic conductivities. Similar benefit was not realized for the NaB GCL, which had similar hydraulic conductivity for tests with low and high initial stress, except for the test at 200 kPa.

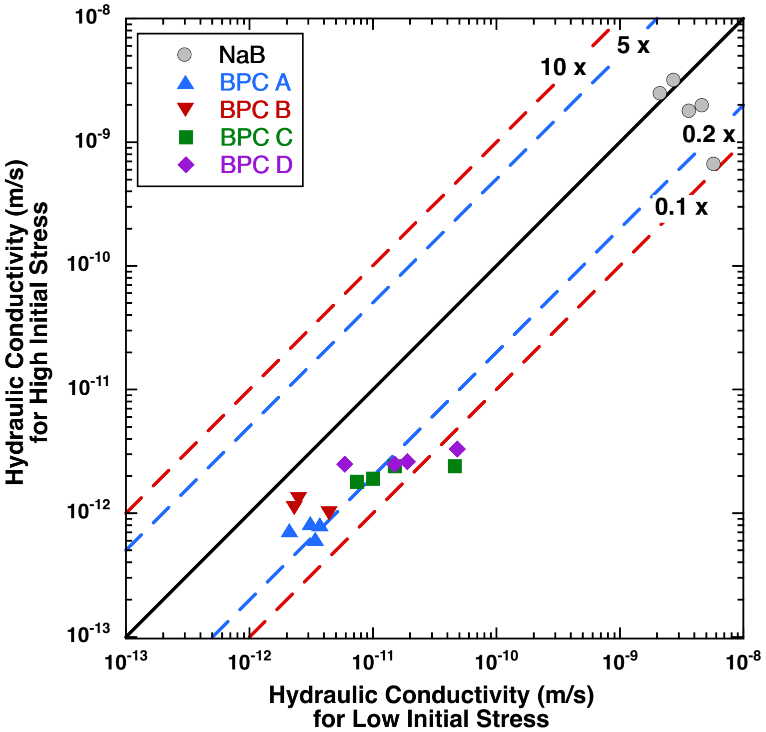

Figure 4: Hydraulic conductivity of NaB GCLs and BPC GCLs for tests conductedat high initial stress (200 kPa) vs. low initial stress (20 kPa)

Efficacy of swell index and active water content

Efficacy of SI and AWC as indicators of the hydraulic conductivity of the NaB and BPC GCLs to the copper heap leach solution is shown in Figure 5 using data from the low initial stress tests at 20 kPa along with data reported in Tan et al. (2022) (black dots). The data from the tests in this study are consistent with the data reported in Tan et al. (2022). The lowest hydraulic conductivities are realized for the highest SI and AWC, but neither index is effective in discriminating between less permeable and more permeable BPC GCLs. More study is needed to identify indicator tests that are effective predictors of the hydraulic conductivity of BPC GCLs.

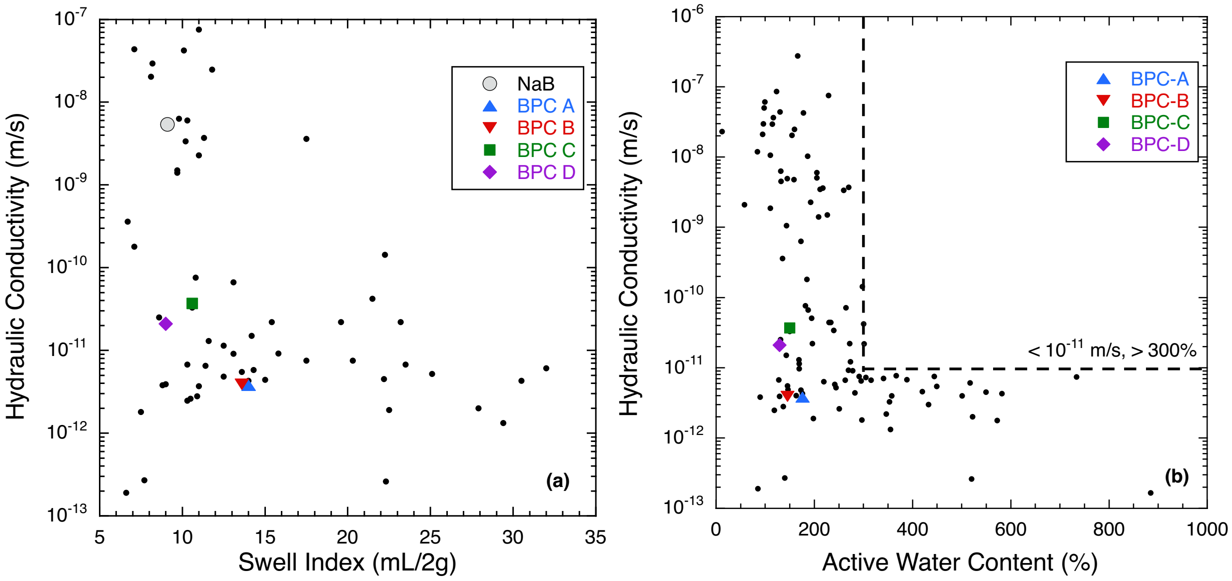

Figure 5: Hydraulic conductivity of GCLs vs. swell index (a) and active water content (b) for NaB or BPC hydrated in copper heap leach solution. Small solid black symbols from Tan et al. (2022)

Summary and conclusions

Hydraulic conductivities of geosynthetic clay liners (GCLs) containing commercially available bentonite-polymer composites (BPCs) or sodium bentonite (NaB) were evaluated using a synthetic copper heap leach solution as the permeant liquid. The BPCs were comprised of granular NaB dry-blended with granular polymer. Each GCL had a unique polymer, with the polymer used in each BPC and the polymer loading proprietary to the manufacturer. The NaB GCL was comprised of the same bentonite used in the BPCs.

The tests were conducted on NaB GCL specimens trimmed from a test roll provided by the manufacturer and on mock BPC GCL specimens prepared from the BPCs and geotextiles provided by the manufacturer. Tests were conducted under two different stress scenarios: low and high initial confining stress. In the low stress scenario, testing began at low initial confining stress (20 kPa) simulating a thin layer of ore on the heap leach pad, followed by a ramp up to as much 600 kPa in seven increments representing increasing ore thickness. The higher stress scenario began with a higher initial confining stress (200 kPa) simulating a 10-m-thick layer of ore rapidly placed on the pad, followed by the same ramp up to as much as 600 kPa. The two scenarios were evaluated to determine if higher stress prior to contact with solution protects the GCL from adverse chemical interactions.

Permeation with the copper heap leach solution adversely affected the Na-bentonite GCL, with the hydraulic conductivity exceeding 10^{-9} m/s for all but one case (200 kPa stress under high initial stress condition). The BPC GCLs had much lower hydraulic conductivities ($< 9\times10^{-11}$ m/s), indicating that BPC GCLs can be more effective than NaB GCLs as liners for copper heap leach pads. The BPC GCLs permeated with higher initial stress had lower hydraulic conductivity at comparable stress compared to those initially permeated at low initial stress, indicating that high initial stress affords protection for BPC GCLs against excessive hydraulic conductivity. Similar protection was not realized for the NaB GCL. Hydraulic conductivity of the BPC GCLs varied between polymers, indicating that efficacy of a BPC GCL for containing leach solutions depends on the polymer employed. Hydraulic conductivity of the BPC GCLs decreased only modestly with increasing effective stress, indicating that the BPC GCLs had very small and tortuous pore spaces.

Swell index (SI) and active water content (AWC) were evaluated as indices of hydraulic conductivity of the BPC GCLs. Data from the tests in this study were consistent with SI and AWC data from past studies on BPC GCLs, but neither index was an effective indicator of hydraulic conductivity of the BPC GCLs. Additional study is needed to identify an appropriate index test for the hydraulic conductivity of BPC GCLs.

Acknowledgement

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